Anomalous J/ψ suppression in Pb-Pb interactions at 158 GeV per nucleon

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NA50 Collaboration

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ABSTRACT. The Drell-Yan and J/ψ cross-sections measured in Pb-Pb collisions are compared with the values extrapolated from the results obtained in proton and light ion induced reactions. While the Drell-Yan production exhibits the normal expected behaviour, the yield of J/ψ in Pb-Pb interactions is abnormally low, as it lies 9 standard deviations below the expected value. Moreover, the departure from the expected behaviour increases significantly from peripheral to central collisions.

1. Introduction

It is now a well established prediction from lattice QCD calculations [1] that, under extreme energy density conditions, ordinary hadronic matter will undergo a phase transition to the so-called Quark-Gluon Plasma (QGP).

The main feature of this phase of matter is that the elementary constituents of hadrons are deconfined, i.e. that quarks and gluons do not form any more individual hadrons and are free to move within the medium. From the very beginning and before the start up of the experimental search in the field, it was pointed out [2] that deconfinement would induce color screening which in turn would prevent J/ψ formation, making of "J/ψ suppression" one of the gold-plated signatures for QGP experimental evidence. Starting from 1986 on, high energy ion beams (O, S and finally Pb) became available at CERN. They made possible the search for QGP formation in ultrarelativistic nucleus-nucleus collisions where it was believed that the required conditions could be reached at best. Experiment NA38 developed an extensive program studying charmonium in p-A and A-B reactions with incident proton, oxygen and sulfur ions on different nuclear targets. The results obtained for J/ψ production [3] led to a solid systematic experimental reference. They triggered a considerable amount of theoretical work [4] and can be understood, according to some authors, in an overall coherent framework [5].

In this letter, we compare the Pb-Pb values measured by the NA50 experiment, as reported in the preceding letter [6], with the values previously obtained with lighter incident ions.

2. Drell-Yan cross-sections

The behaviour of the Drell-Yan cross-section in Pb-Pb collisions is compared with the values obtained in p-p, p-d, p-W and S-U interactions with the same basic spectrometer [7]. For the various systems, the kinematical domains are not strictly identical on one hand and, on the other, the incident momentum (and thus $\sqrt{s}$) is significantly different i.e., 450 GeV/c for p-p and p-d and 200 GeV/c for p-W and S-U. The comparison is therefore made using the so-called K-factor which accounts for higher order corrections to the lowest order Drell-Yan theoretical cross-section. We thus compute, for each system

$$K_{DY} \;=\; \sigma^{DY}_{exp} \;/\; \sigma^{DY}_{GRV-LO}$$

where σ^{DY}_{exp} is the measured value of the cross-section and σ^{DY}_{GRV-LO} the lowest order Drell-Yan cross-section computed, with the appropriate $\sqrt{s}$ and in the same kinematical domain, using the GRV-LO [8] set of parton distribution functions.

The results are listed in Table 1 and plotted in figure 1 as a function of the product AB of the target and projectile atomic mass numbers. They all show good agreement both with each other and with the well known Drell-Yan theoretical calculations. In particular, the Pb-Pb Drell-Yan cross-section determined as detailed above, exhibits a behaviour which is fully compatible with expectations from other experiments.

3. J/ψ cross-sections

The results obtained for the Drell-Yan process show the absence of any significant bias in our absolute cross-section measurements. We can now compare the J/ψ production cross-section in Pb-Pb interactions with values obtained previously with different beam and target combinations with the same spectrometer. For this purpose, we calculate the "cross-section per nucleon-nucleon collision", i.e. the cross-section divided by the product AB of the projectile and target atomic mass numbers. The values obtained under different experimental conditions are rescaled to 200 GeV/c incident momentum and recomputed, if necessary, in the kinematical domain $\mathcal{D}$

defined by:

$$0 \leq y_{cms} \leq 1 \qquad \text{and} \qquad |\cos\theta_{CS}| < 0.5$$

All the values obtained with the 450 GeV/c data (p-p, p-d, p-C, p-Al, p-Cu and p-W), are globally scaled down with the same factor using the following procedure. First, the 450 GeV/c and 200 GeV/c data are fitted independently, assuming that the J/ψ cross-section is proportional to $(AB)^\alpha$. The results are respectively $\alpha = 0.92 \pm 0.02$ and $\alpha = 0.91 \pm 0.03$. Their good compatibility justifies a simultaneous fit to the 450 GeV/c and 200 GeV/c data imposing the same value of α for the two samples, which gives $\alpha = 0.920 \pm 0.015$, in fair agreement with previous p-A results [9]. The global rescaling factor obtained from this fit is 0.406 ± 0.038, to be compared with the value 0.418 ± 0.083 which would result from the x_F and $\sqrt{s}$ dependence of the J/ψ cross-section as given by the Schuler parametrization [10]. The "rescaled" 450 GeV/c data together with the 200 GeV/c data are plotted in figure 2 which also shows the result of the simultaneous exponential fit described above.

The Pb-Pb "cross-section per nucleon-nucleon collision" measured in the NA50 experiment is 0.51 ± 0.04 nb [6]. As already obtained in the domain $\mathcal{D}$, it only needs a $\sqrt{s}$ correction which is calculated from the Schuler parametrization [10]. The correction factor is 1.32 ± 0.04, and the corresponding cross-section value is 0.67 ± 0.05 nb.

The results are listed in Table 2 and plotted in figure 2 as a function of AB. The Pb-Pb result is about 5 standard deviations off the fitted function and lies below the expected value by a factor

$$R_K^{cross-section} = 0.74 \pm 0.06.$$

This is a first hint that J/ψ production is anomalously suppressed in Pb-Pb interactions.

According to [5] the "normal" behaviour of J/ψ production which corresponds to a value of the exponent α close to 0.91, can be interpreted as the result of the break-up of a pre-resonant object meant to become later on, if not destroyed, the fully formed resonant J/ψ state. Within this interpretation, the J/ψ production cross-section can be written to the first order as

$$\sigma(AB \to J/\psi) \ \propto \ (AB) \ \exp\left(-\rho_0 \ \sigma_{abs} \ \bar{L}\right) \tag{1}$$

where (AB) accounts for the $(c\bar{c})$ creation probability in A-B collisions and the decreasing exponential for its break-up probability, with cross-section σ_{abs}, along its path through nuclear matter. The parameter $\rho_0 \ = \ 0.17 \ \mathrm{fm}^{-3}$ is the nuclear matter standard average density. For any given p-A or A-B system, $\bar{L}$ stands for the mean length of the path of the $(c\bar{c})$ system through nuclear matter of mean density ρ_0:

$$\bar{L} \ = < \bar{L}(b) > .$$

At a given impact parameter b, $\bar{L}(b)$ can be calculated as:

$$\bar{L}(b) \ = \ \frac{1}{\rho_0} < \int \rho \, dz > .$$

For a given position of the $(c\bar{c})$ pair creation point inside the colliding nuclei, the integral is taken along the potential path of the $(c\bar{c})$ system through these nuclei. The average takes into account all possible positions, for a given value of b, of the $(c\bar{c})$ pair creation point, weighted by the probability to create it at that point.

In previous reports of preliminary results of the NA50 experiment [11], $\bar{L}$ was calculated assuming for $\rho(r)$ the sharp-surface approximation[1]. In this paper, we choose the standard three-parameter Woods-Saxon form with numerical parameters from [12]. Anyway, it should

[1] In this particular case, for a projectile and a target of atomic mass numbers A_p and A_t respectively, *when integrated over the impact parameter*, $\bar{L}$ is simply given by $\bar{L} = \bar{L}_p + \bar{L}_t$ with $\bar{L}_{p,t} = 3/4 \ r_0 \ \frac{A_{p,t}-1}{A_{p,t}} A_{p,t}^{1/3}$ and $r_0 = 1.1$ fm

be stressed that the exact choice of the nuclear density model does not affect the essential features of our results. Figure 3 shows, as a function of $\bar{L}$, the same "cross-sections per nucleon-nucleon collision" as figure 2. The simultaneous fit of the expression given in equation (1) to the 450 GeV/c and 200 GeV/c data leads to $\sigma_{abs} = 6.2 \pm 1.1$ mb when the Pb cross-section is excluded from the fit. The significant departure of the Pb value from the fitted exponential function is a clear evidence that the J/ψ suppression observed in Pb-Pb interactions cannot be anymore accounted for by nuclear absorption effects.

4. J/ψ cross-section as a function of the centrality of the collision.

In this section, we make use of the fact that the Drell-Yan cross-section scales with the number of nucleon-nucleon collisions, as once more confirmed with the present data. This scaling feature requires in fact that the measured Drell-Yan cross-sections be corrected to account for the relative amount of interacting protons and neutrons, as the Drell-Yan mechanism depends on the isospin of the nucleon. We therefore correct for this "isospin effect" and replace the measured Drell-Yan cross-section by:

$$\sigma^{DY}_{corr} = \sigma^{DY}_{meas} \frac{(AB)\,(\sigma^{DY}_{GRVLO})_{pp}}{(\sigma^{DY}_{GRVLO})_{AB}}$$

which is equivalent to the Drell-Yan cross-section we would have measured for the same two nuclei were they only made of protons. This procedure leads to the following correction factor:

$$\sigma^{DY}_{corr}/\sigma^{DY}_{meas} = 1.30$$

This corrected Drell-Yan cross-section, deduced from our measurement, should be proportional to the product AB so that the ratio of cross sections $\sigma_{J/\psi}$ / σ_{DY} is now strictly proportional to the J/ψ "cross-section per nucleon-nucleon collision".

The values of the ratio $\sigma_{J/\psi}$ / σ_{DY}, rescaled[1] to 200 GeV/c, with the Drell-Yan cross-section taken in the mass interval 2.9-4.5 GeV/c^2 and corrected for "isospin effect", are listed in table 3 as a function of the average $\bar{L}$ of $\bar{L}(b)$ in each E_T bin. The value of $\bar{L}$ in each bin is calculated from the $\bar{L} - E_T$ correlation presented in figure 4. This correlation results from the $\bar{L}(b)$ dependence on b and from the $b - E_T$ correlation shown in the preceding letter [6].

The ratio of cross-sections $\sigma_{J/\psi}/\sigma_{DY}$ is plotted in figure 5 as a function of $\bar{L}$ in each of the five E_T bins. The ratios of J/ψ to Drell-Yan cross-sections measured in NA38 and NA51 experiments are also presented in figure 5. The p-W, p-U and S-U measurements, all done at 200 GeV/c incident momentum, are well fitted by an exponentially decreasing law and lead to an absorption cross-section of 6.1 $\pm$ 0.7mb, in perfect agreement with the value already obtained from the data[2] shown in figure 3. This exponential behaviour, characteristic of nuclear absorption, holds from p-p until the most central S-U interactions. It breaks down for values of $\bar{L}$ immediately higher.

The departure of the Pb data from the absorption-like behaviour as observed in proton and light ion induced reactions can be quantified using the ratio

$$R_K^{J/\psi/DY}(\bar{L}) = \frac{(\sigma_{J/\psi}\ /\ \sigma_{DY})_{measured}}{(\sigma_{J/\psi}\ /\ \sigma_{DY})_{absorption}}$$

which is given for each E_T bin in table 3. The errors quoted in this table for the values of R_K include the systematic uncertainty related to the normalization of the open charm contribution, as mentioned in ref. [6].

It is of interest to notice that the value obtained in the first bin (for the most peripheral

[1]The scaling factor for Drell-Yan cross-section from 158 GeV/c to 200 GeV/c amounts to 1.31 in the mass range 2.9-4.5 GeV/c^2.

[2]When including the p-p and p-d measurements, the fitted value is 5.9 ± 0.7 mb.

reactions)

$$R_K^{J/\psi/DY}(\,5\,\mathrm{GeV} < E_T < 45\,\mathrm{GeV}\,) \;=\; 0.95 \;\pm\; 0.09$$

is fully compatible with the absorption model expectation.

The J/ψ to Drell-Yan cross-section ratio has also been measured for the full sample of events, whatever the centrality [6]. The result, corrected for the "isospin effect", is:

$$B_{\mu\mu}\,\sigma_{J/\psi}\;/\;\sigma_{DY} = 12.4\;\pm\;0.2\;\pm 0.2$$

This ratio leads to

$$R_K^{J/\psi/DY}(All\,E_T) = 0.71\;\pm\;0.03$$

showing that the J/ψ yield in Pb-Pb interactions is 9 standard deviations away from the value expected from pure nuclear absorption. It is also worthwhile underlining the remarkable agreement of our most accurate estimate of R_K, deduced from the ratio of J/ψ to Drell-Yan cross-sections, with the value obtained from our absolute J/ψ cross-section measurement:

$$R_K^{cross-section} = 0.74\,\pm\,0.06.$$

5. Conclusion

It has been predicted that J/ψ suppression would unambiguously sign the quark gluon plasma formation which, as a phase transition, would normally exhibit observable discontinuities.

There is now an extensive set of experimental results obtained so far by the NA38 collaboration as well as by other proton experiments, both for J/ψ and ψ' production in proton-nucleus and nucleus-nucleus interactions. An overall coherent picture arises from this set of results. This picture is quantitatively fully consistent with a mechanism which attributes to nuclear absorption of a pre-resonant state the past observed J/ψ "suppression". The study of Pb-Pb interactions in 158 GeV per nucleon incident momentum shows a clear departure of the J/ψ production rate from the absorption behaviour, as experimentally observed with lighter incident projectiles up to sulphur. Integrated on impact parameter, the measured J/ψ production rate is a factor 0.71 ± 0.03 below the value expected from nuclear absorption as extrapolated from previous experimental results. The most central interactions are a factor 0.62 ± 0.04 below the expected value. This effect probably requires the onset of a very dense state of matter together with very specific matter properties to be accounted for.

As already mentioned, several authors [14] attribute this very peculiar overall behaviour to the onset of some new physics. Others have developed scenarios which quantitatively reproduce the features of the data up to S-U reactions [5], but fail to explain the Pb-Pb data. More recent works [15] consider also interactions with comovers and are able to approach qualitatively the experimental Pb-Pb results. However, they poorly reproduce the results obtained so far for lighter projectiles and proton-induced reactions, whereas a good agreement with these data should be obviously a prerequisite of any explanation of the results presented in this paper.

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$Projectile - target$	AB	$K \ - \ factor$
$p - p$	1	$2.27 \pm 0.06 \pm 0.16$
$p - d$	2	$2.71 \pm 0.07 \pm 0.19$
$p - W$	184	$2.42 \pm 0.16 \pm 0.24$
$S - U$	7616	$2.24 \pm 0.03 \pm 0.18$
$Pb - Pb$	43100	$2.56 \pm 0.04 \pm 0.18$

Table 1
The Drell-Yan K-factor. Measurements were done at 450 GeV/c for p-p and p-d (experiment NA51), 200 GeV/c for p-W and S-U (experiment NA38) and 158 GeV/c for Pb-Pb (experiment NA50).

$Reaction$	$P_{lab}(per\ nucl.)$ (GeV/c)	AB	$\bar{L}$ (fm)	$B_{\mu\mu}\sigma_{J/\psi}$ / AB (nb)
$p-p$	450	1	0.00	2.10 ± 0.15
$p-d$	450	2	0.13	2.19 ± 0.16
$p-C$	450	12	1.22	1.79 ± 0.14
$p-Al$	450	27	1.89	1.60 ± 0.14
$p-Cu$	450	63	2.62	1.62 ± 0.13
$p-Cu$	200	63	2.62	1.69 ± 0.41
$p-W$	450	184	3.94	1.44 ± 0.11
$p-W$	200	184	3.94	1.43 ± 0.15
$p-U$	200	238	4.57	1.40 ± 0.35
$O-Cu$	200	1008	3.98	1.28 ± 0.17
$O-U$	200	3808	5.92	1.19 ± 0.16
$S-U$	200	7616	6.49	1.02 ± 0.11
$Pb-Pb$	158	43100	8.57	0.67 ± 0.05

Table 2
The J/ψ cross-section divided by AB, in nb units, rescaled to 200 GeV/c and recomputed in the kinematical domain $\mathcal{D}$ from experiments NA38, NA51 and NA50.

E_T *bin range* (GeV)	$\bar{L}$ (fm)	$B_{\mu\mu}\sigma_{J/\psi}$ / σ_{DY}	R_K
$5-45$	6.94 ± 0.49	19.7 ± 1.6	0.95 ± 0.09
$45-70$	7.98 ± 0.36	14.4 ± 0.7	0.77 ± 0.05
$70-105$	8.86 ± 0.30	13.8 ± 0.3	0.81 ± 0.03
$105-135$	9.43 ± 0.17	10.9 ± 0.3	0.68 ± 0.03
$135-175$	9.71 ± 0.15	9.7 ± 0.4	0.62 ± 0.04
All E_T	8.57	12.4 ± 0.2	0.71 ± 0.03

Table 3
The ratio of the J/ψ to the Drell-Yan cross-section as a function of centrality, rescaled at 200 GeV/c. The Drell-Yan cross-section is corrected for the "isospin effect" as explained in the text and taken in the mass range 2.9-4.5 GeV/c^2. The values of $\bar{L}$ correspond to the average of $\bar{L}(b)$ for the events observed in each bin. For each E_T bin, the width of the corresponding $\bar{L}$ distribution is given. In the last line presenting the results averaged over E_T, the values are corrected to take into account the subtarget identification inefficiency.

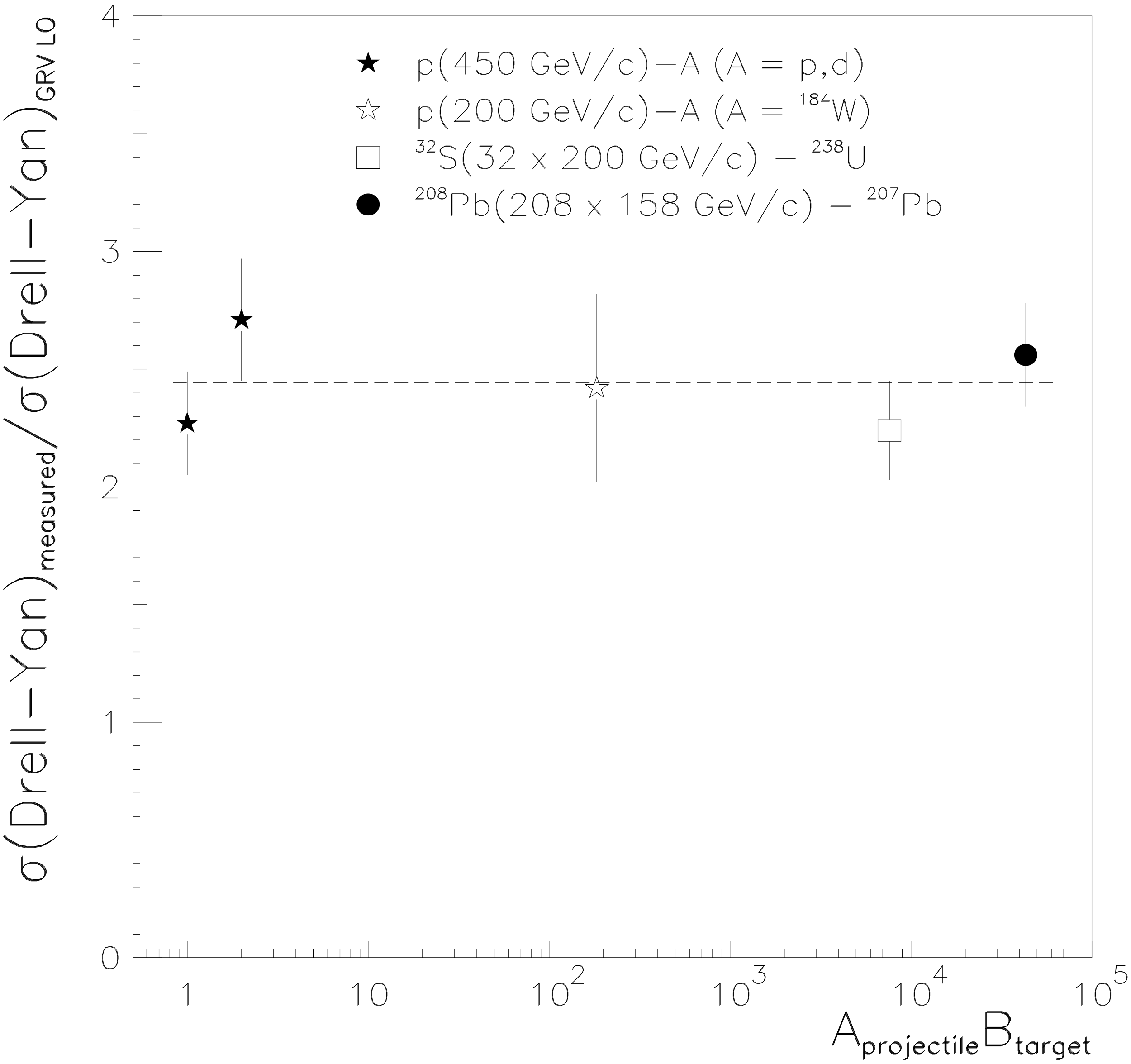

Fig. 1. The Drell-Yan K-factor as a function of the product AB of the projectile and target atomic mass numbers. The dashed line shows the average value of the data.

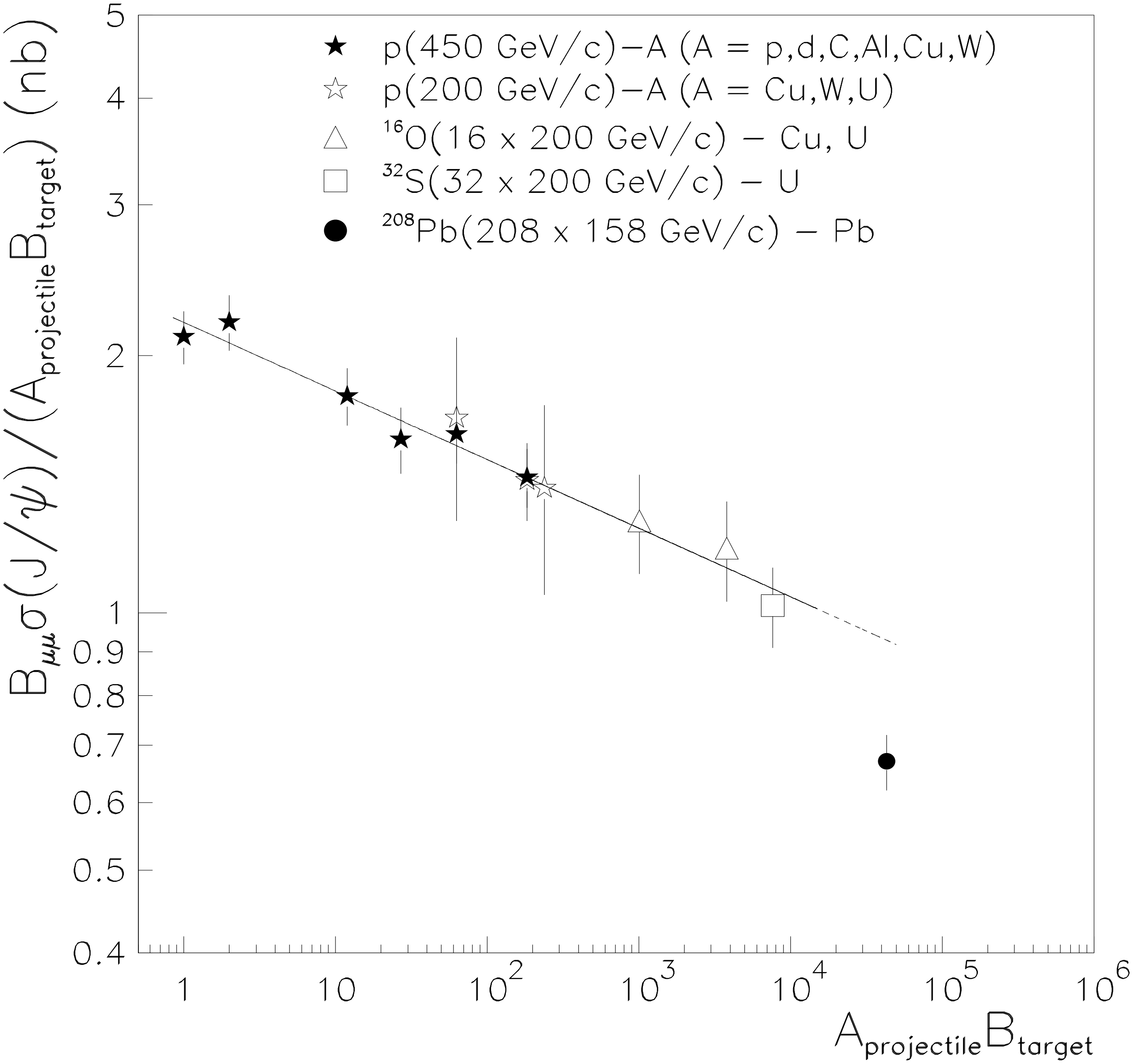

Fig. 2. The J/ψ "cross-section per nucleon-nucleon collision"as a function of the product AB of the projectile and target atomic mass numbers. The results obtained at 450 GeV/c and the Pb-Pb cross-section are rescaled as explained in the text.

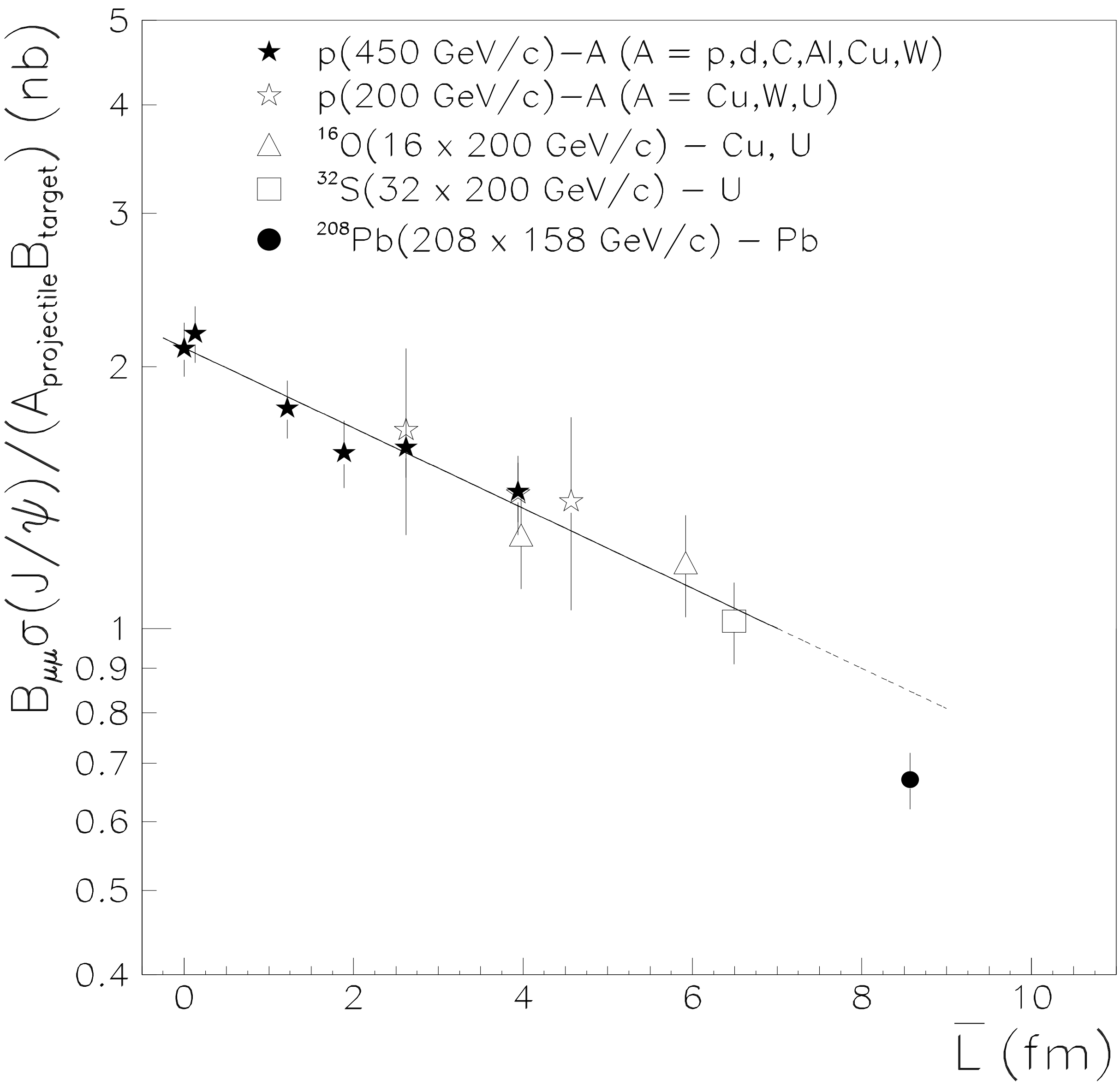

Fig. 3. The J/ψ "cross-sections per nucleon-nucleon collision" as a function of $\bar{L}$. The results obtained at 450 GeV/c and the Pb-Pb cross-section are rescaled as explained in the text.

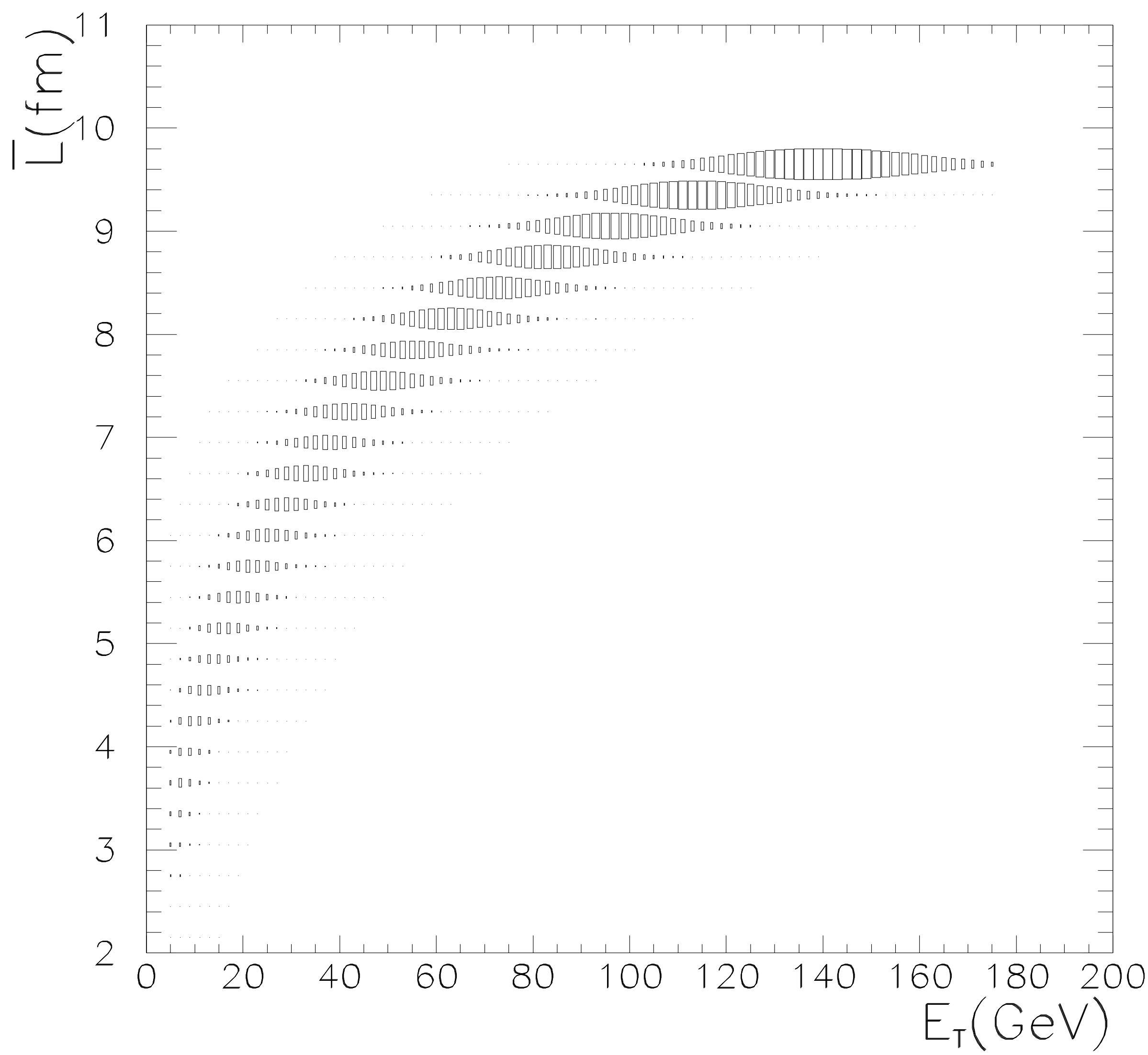

Fig. 4. Correlation between E_T and $\bar{L}$ calculated for Pb-Pb collisions at 158 GeV/c for Drell-Yan events.

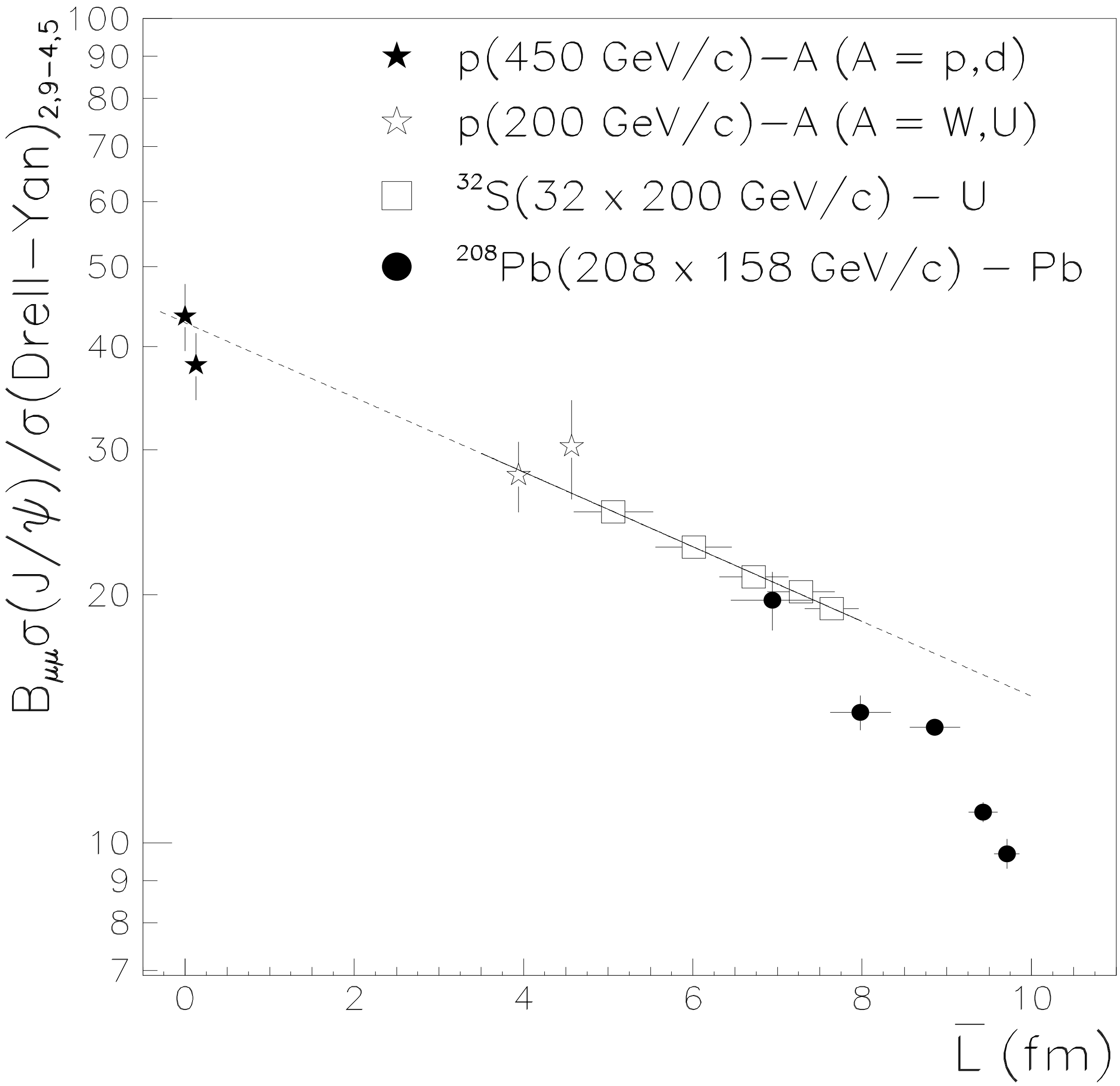

Fig. 5. The ratio of J/ψ to Drell-Yan cross-sections as a function of $\bar{L}$.